(7) IN/34 0098

A MECHANISTIC STUDY OF NUCLEATE BOILING HEAT TRANSFER UNDER MICROGRAVITY CONDITIONS

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ABSTRACT

Experimental studies of growth and detachment processes of a single bubble and multiple bubbles formed on a heated surface have been conducted in the parabola flights of KC-135 aircraft. Distilled water and PF5060 were used as the test liquids. A micro-fabricated test surface was designed and built. Artificial cavities of diameters 10 μm, 7 μm and 4 μm were made on a thin polished Silicon wafer that was electrically heated by a number of small heating elements on the back side in order to control the surface superheat.

Bubble growth period, bubble size and shape from nucleation to departure were measured under subcooled and saturation conditions. Significantly larger bubble departure diameters and bubble growth periods than those at earth normal gravity were observed. Bubble departure diameters as large as 20 mm for water and 6 mm for PF5060 were observed as opposed to about 3 mm for water and less than 1 mm for PF5060 at earth normal gravity respectively. It is found that the bubble departure diameter can be approximately related to the gravity level through the relation $D_d \propto 1/\sqrt{g}$. For water, the effect of wall superheat and liquid subcooling on bubble departure diameter is found to be small. The growth periods are found to be very sensitive to liquid subcooling at a given wall superheat. However, the preliminary results of single bubble dynamics using PF5060 showed that the departure diameter increases when wall superheat is elevated at the

same gravity and subcooling. Growth period of single bubbles in water has been found to vary as $t_g \propto g^{-0.93}$.

For water, when the magnitude of horizontal gravitational components was comparable to that of gravity normal to the surface, single bubbles slid along the heater surface and departed with smaller diameter at the same gravity level in the direction normal to the surface. For PF5060, even a very small horizontal gravitational component caused the sliding of bubble along the surface.

The numerical simulation has been carried out by solving under the condition of axi-symmetry, the mass, momentum, and energy equations for the vapor and the liquid phases. In the model the contribution of micro-layer has been included and instantaneous shape of the evolving vapor-liquid interface is determined from the analysis. Consistent with the experimental results, it is found that effect of reduced gravity is to stretch the growth period and bubble diameter It is found that effect of reduced gravity is to stretch the growth period and bubble diameter at departure. The numerical simulations are in good agreement with the experimental data for both the departure diameters and the growth periods.

In the study on dynamics of multiple bubbles, horizontal merger of 2, 3 4, and 5 bubbles was observed. It is found that after merger of 2 and 3 bubbles the equivalent diameter of the detached bubble is smaller than that of a single bubble departing at the same gravity level. During and after bubble merger, liquid still fills the space between the vapor stems so as to form mushroom type bubbles.

The experimental and numerical studies conducted so far have brought us a step closer to prediction of nucleate boiling heat fluxes under low gravity conditions. Preparations for a space flight are continuing.

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Presented at the

FIFTH MICROGRAVITY FLUID PHYSICS AND TRANSPORT PHENOMENA CONFERENCE

August 9-11, 2000, Cleveland, Ohio

OBJECTIVES

- **Mechanistic understanding of low gravity nucleate pool boiling process through numerical simulations and experiments.**
- **Investigation of the scaling of the effect of gravity on the growth and departure of single bubble from a designed nucleation site.**
- **Effect of liquid subcooling and wall superheat on bubble growth and departure at low gravity.**
- **Understanding of horizontal merger process of multiple bubbles at low gravity.**
- **Validation of the predictive model of nucleate boiling under low gravity conditions.**

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NUMERICAL SIMULATIONS

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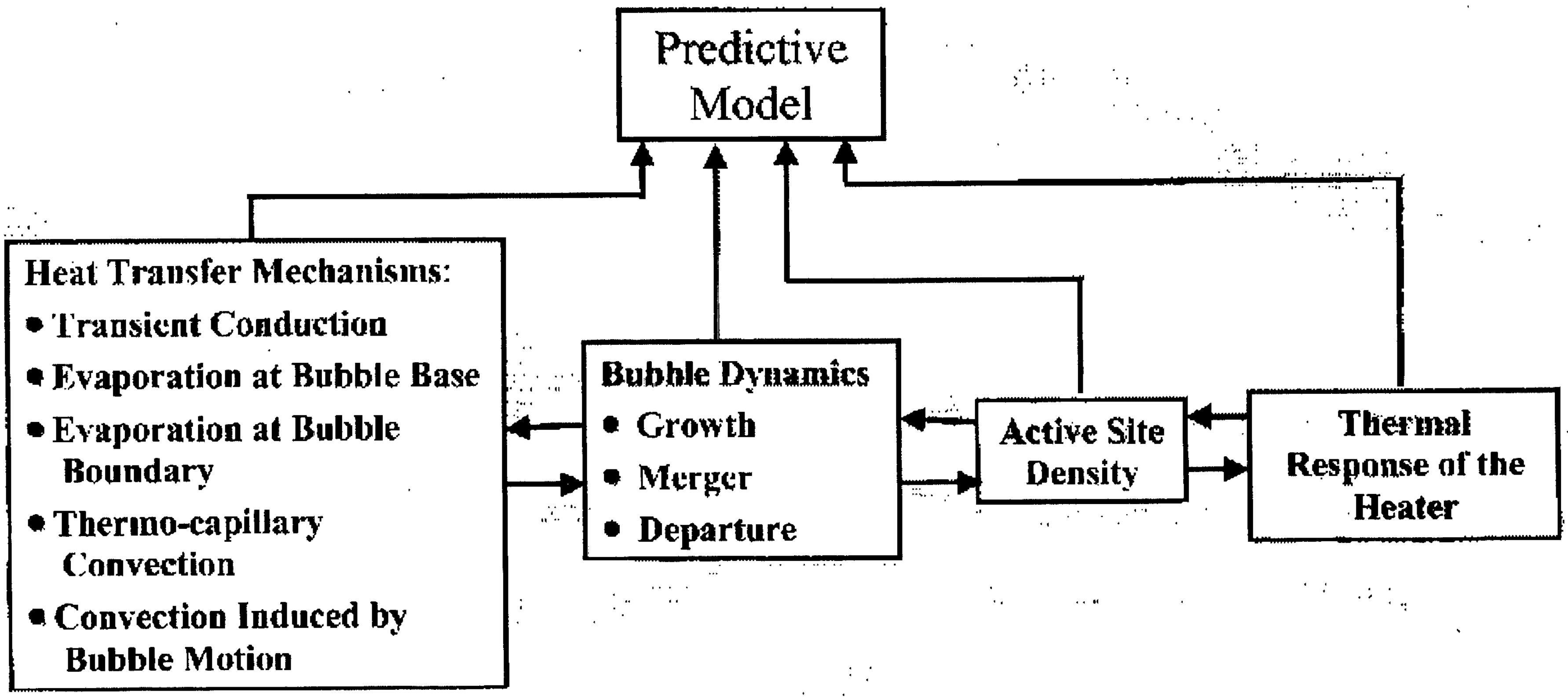
NUMERICAL SIMULATIONS

Prediction of Nucleate Boiling Heat Transfer



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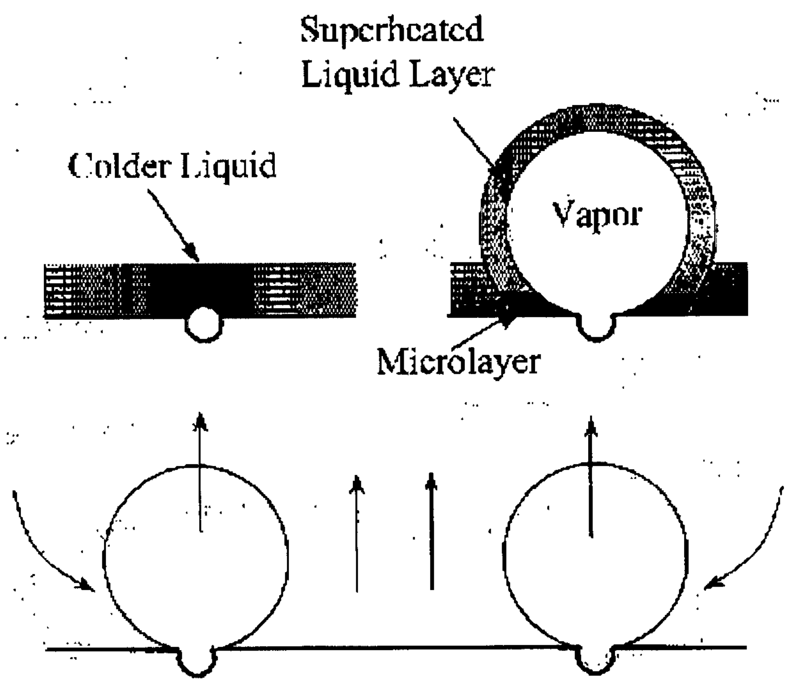
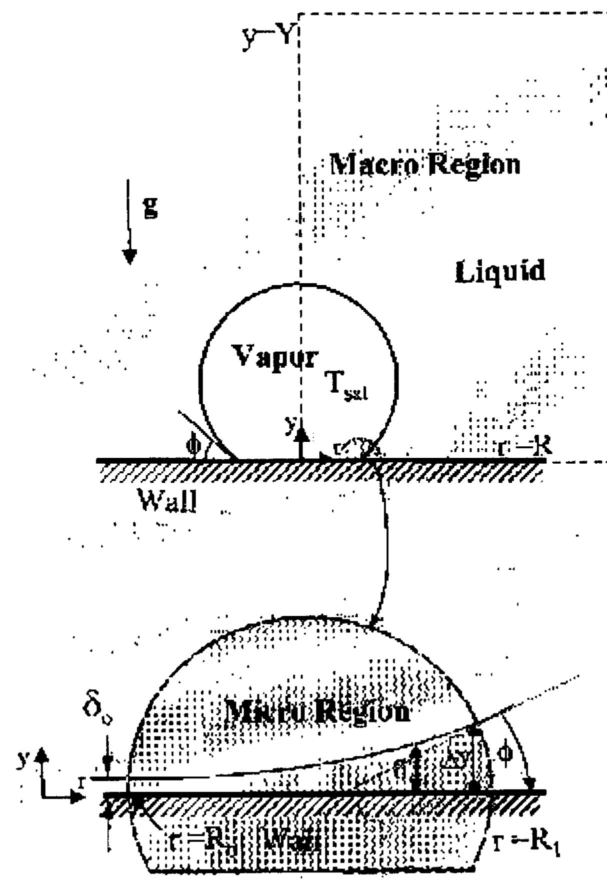
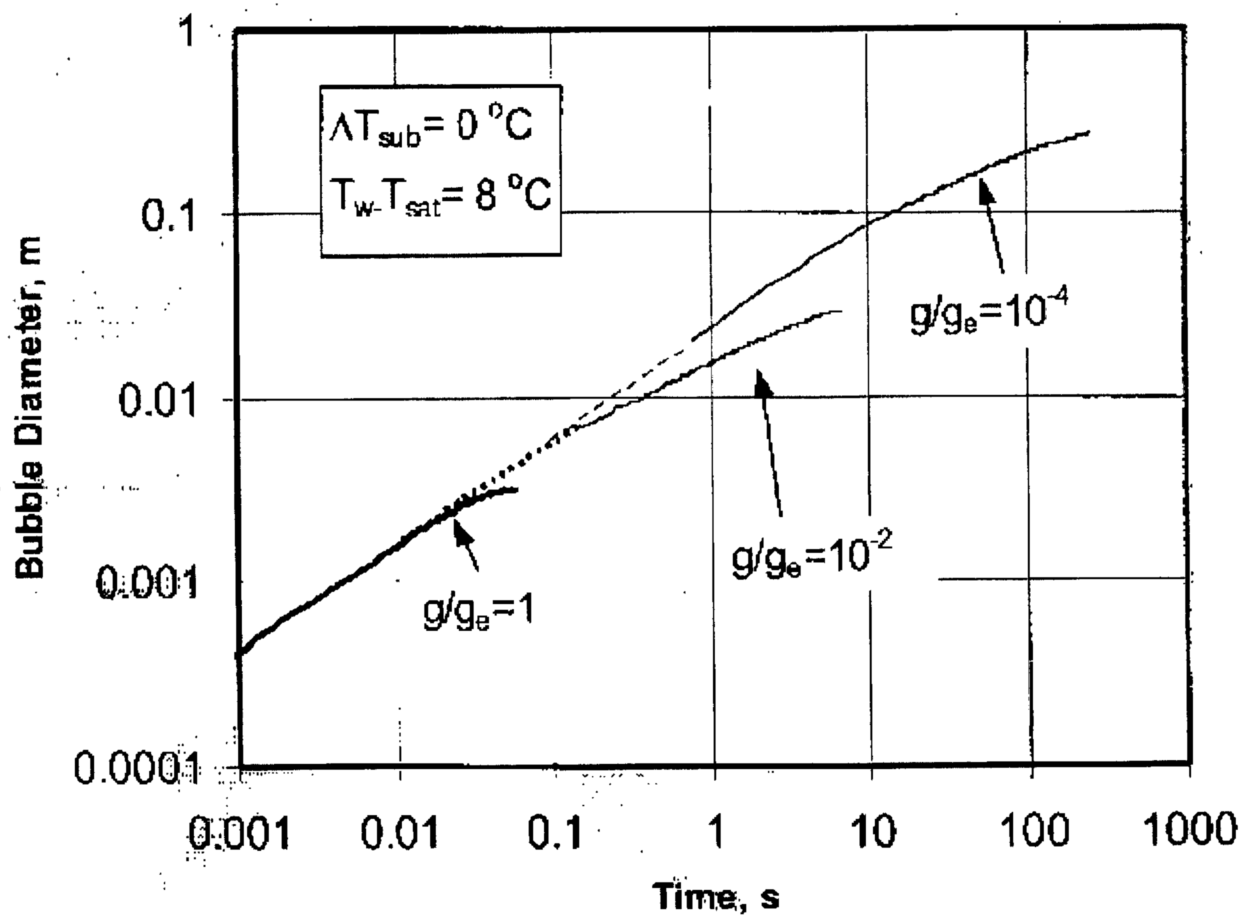
NUMERICAL SIMULATIONS (Cont'd)





NUMERICAL SIMULATIONS (Cont'd)

Predicted Bubble Growth at Different Gravity Levels

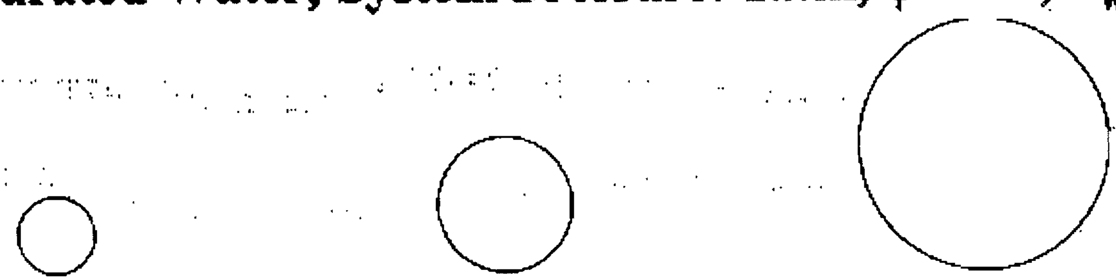


NUMERICAL SIMULATION (Cont'd)

Numerical Simulations - Scaling with Respect to Gravity

Gravity Level	Bubble Departure Diameter (mm)	Bubble Growth Period (sec.)
$1g_e$	2.8	0.056
$10^{-2}g_e$	27	4.5
$10^{-4}g_e$	265	257

Liquid: Saturated Water; System Pressure: 1atm, $\varphi = 50^\circ$, T_w-T_{sat} = 7°C



$1\ g_e$ $10^{-2}\ g_e$ $10^{-4}\ g_e$

$$D_d \propto g^{-1/2} \qquad t_g \propto g^{-0.93}$$

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EXPERIMENTS

EXPERIMENTS

- **Closed Test Chamber:**
  Feedback control of system pressure, liquid subcooling and superheat of heater surface.

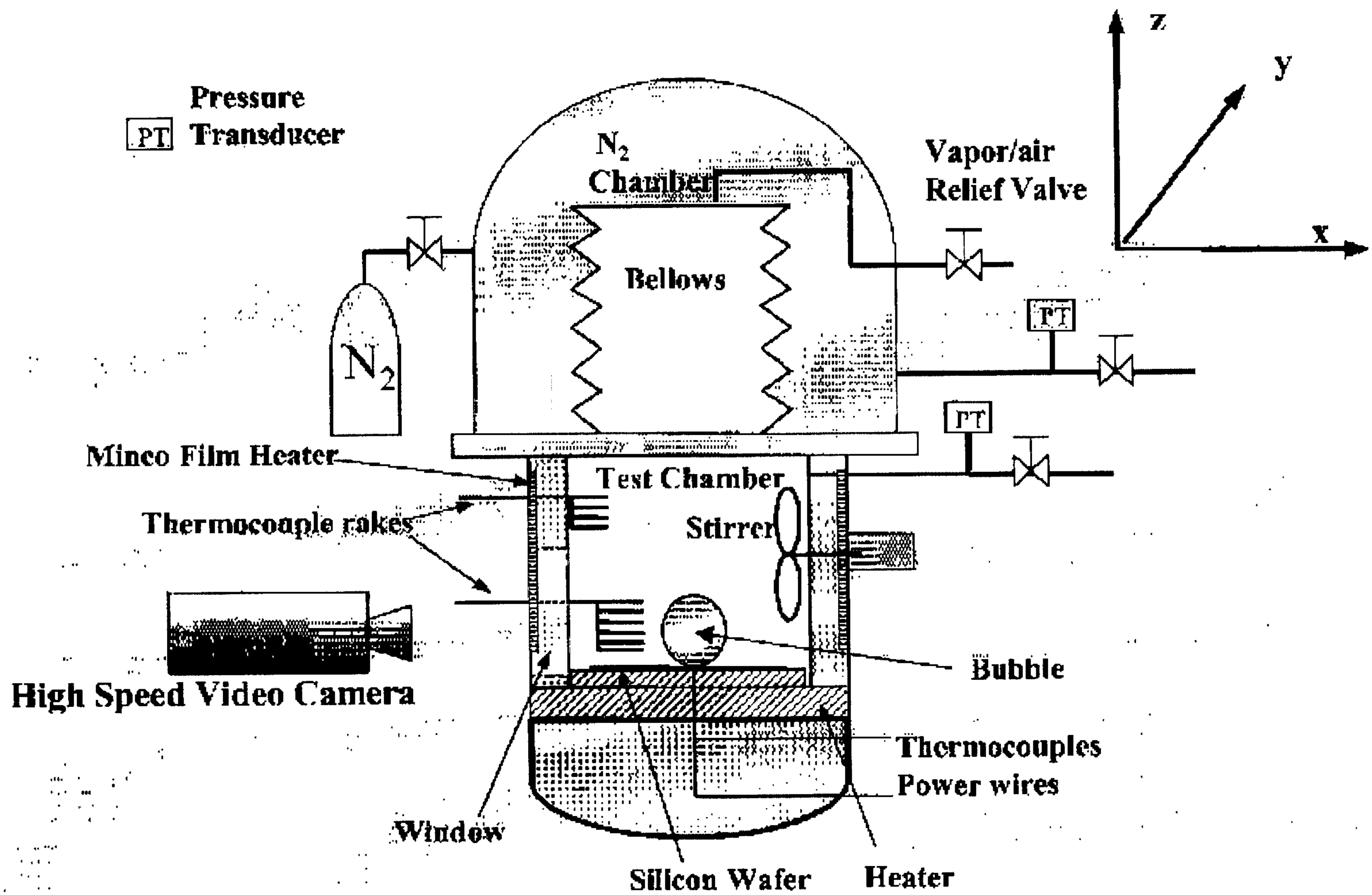
- **Measurements Using Thermocouple Rakes:**
  Liquid temperature near heater surface (thermal boundary layer) and bulk liquid temperature.

- **High Speed Video Cameras:**
  Record the boiling process at large magnification and in two orthogonal directions.

- **Low Gravity Condition during KC-135 Flight:** $g_z \approx \pm 0.04\, g_e$
  in the direction, z, normal to the heater surface with the accidental increase up to 0.065 g_e.

- **Three-Component Accelerometer.**

EXPERIMENTS



Schematic of Experimental Set-up

EXPERIMENTS (Cont'd)

- **Heater Surface:**
  Polished Silicon wafer (roughness < 5 Å).
- **Nucleation Sites:**
  5 Cavities of 100 μm in depth and 10 μm (one), 7 μm (two), 4 μm (two) in diameter at a spacing of 7 mm made in the wafer center via the Deep Reactive Ion Etching Technique.
- **Heating Elements:**
  Foil-like strain gages bonded at the back of silicon wafer and grouped in different regions for separate control of superheats.
- **Nucleation Activation:**
  Only at the desired cavities before take-off of KC-135.
- **Overall Wall Superheat and Bulk Liquid Subcooling:**
  Set to specified values prior to each parabola (low gravity period).

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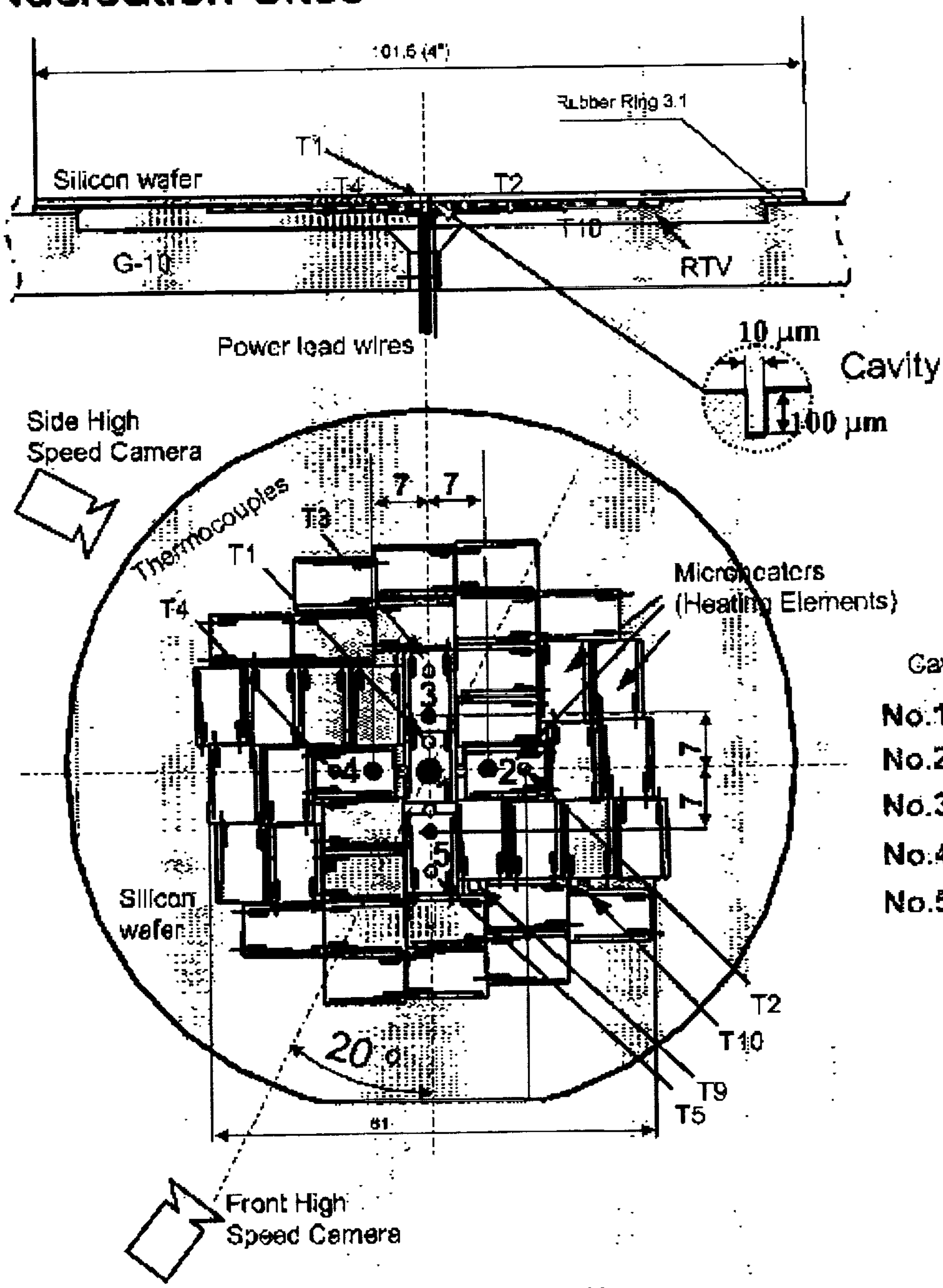
EXPERIMENTS (Cont'd)

Configuration of Heater with Designed Nucleation Sites



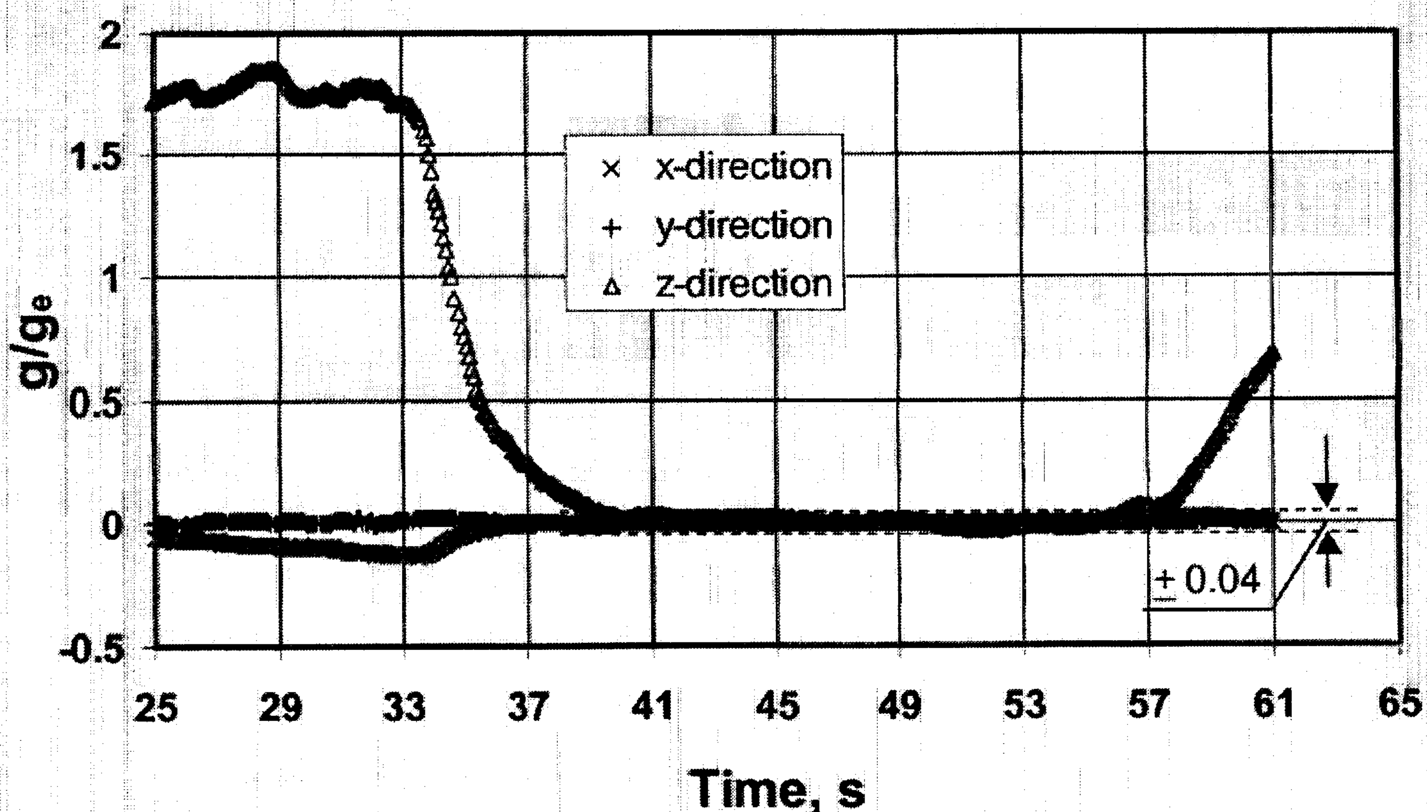
Gavity Size:

No.1:	10 μm
No.2:	7 μm
No.3:	4 μm
No.4:	7 μm
No.5:	4 μm

EXPERIMENTS (Cont'd)

Typical Gravity Level During Parabola Flight

(Run No.389, Oct.6, 1998)



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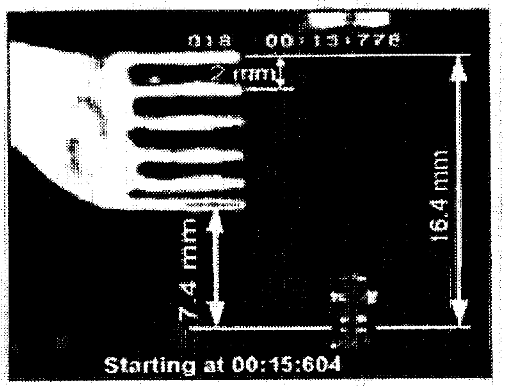
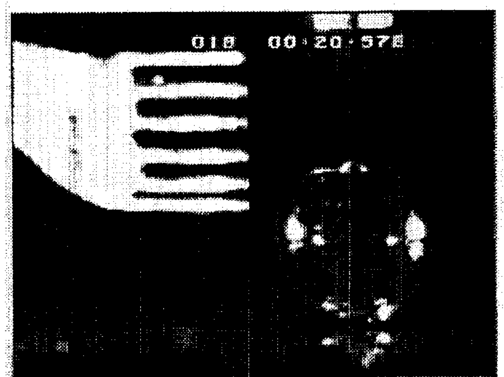
EXPERIMENTAL RESULTS

EXPERIMENTAL RESULTS (Cont'd)

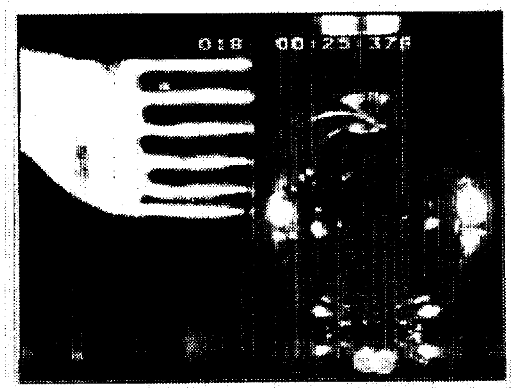
-- Single Bubble at Low Gravity in KC-135



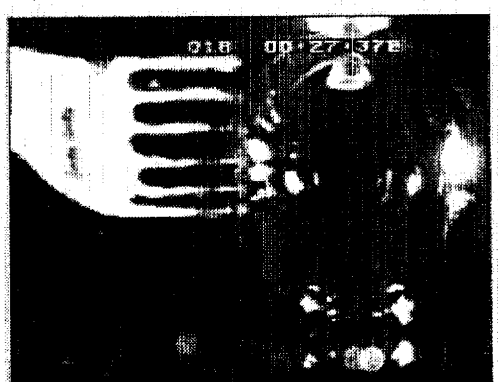
a) t=0.17 s



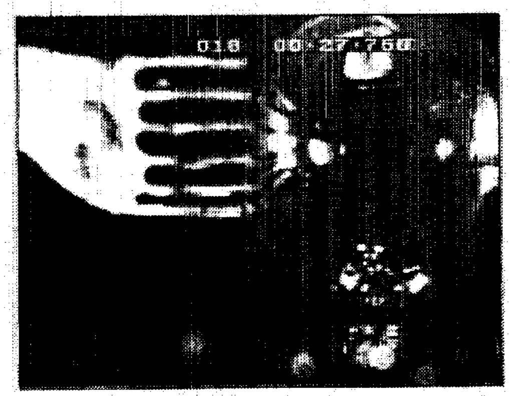
b) t=4.97 s



c) t=9.77 s (maximal base)



d) t=11.77 s



e) t=12.15 (departing)

Pictures of Single Bubble During a Growth-Departure Cycle,
ΔT_{sub}=0.3 °C, T_w-T_{sat}=4.2°C, $g_z \approx 0.02\ g_e$

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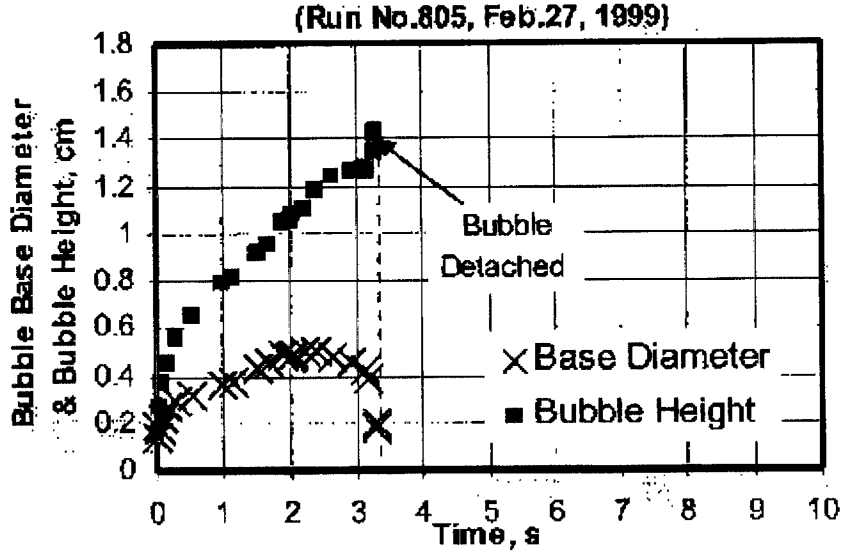
EXPERIMENTAL RESULTS (Cont'd)

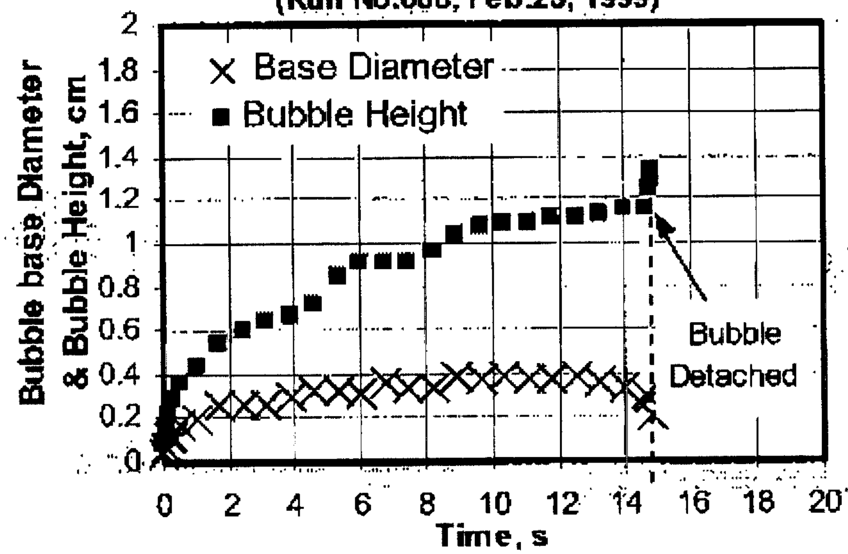
-- Single Bubble at Low Gravity in KC-135

(Run No.805, Feb.27, 1999)



ΔT_{sub}=0.0 °C, T_w-T_{sat}=5.5 °C
$g_z \approx 0.040\ g_e$

(Run No.688, Feb.23, 1999)

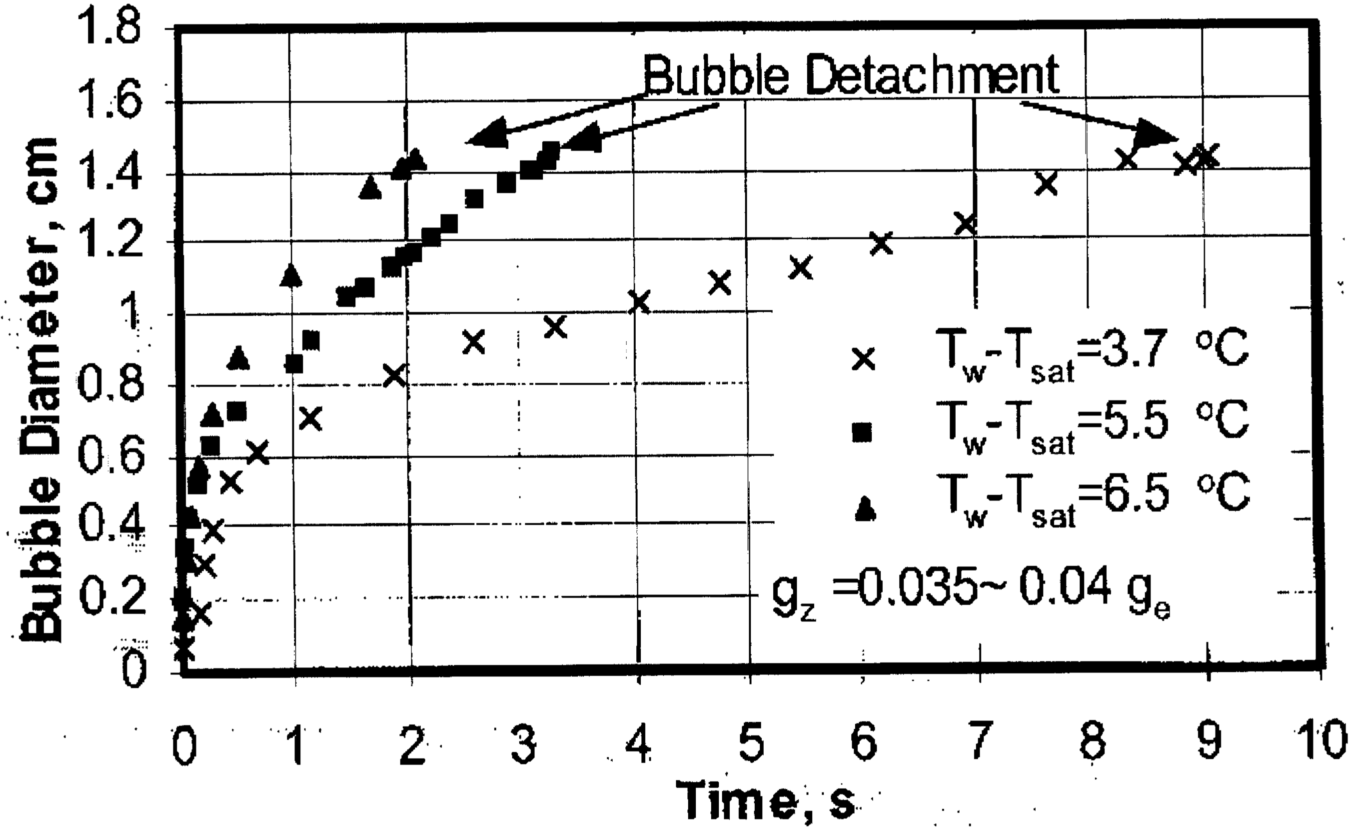


ΔT_{sub}=0.2 °C, T_w-T_{sat}=2.5 °C
$g_z \approx 0.045\ g_e$

Bubble Height and Base Diameter as Function of Time

EXPERIMENTAL RESULTS (Cont'd)

-- Single Bubble at Low Gravity in KC-135



Effect of Wall Superheat on Bubble Growth in Saturated Water

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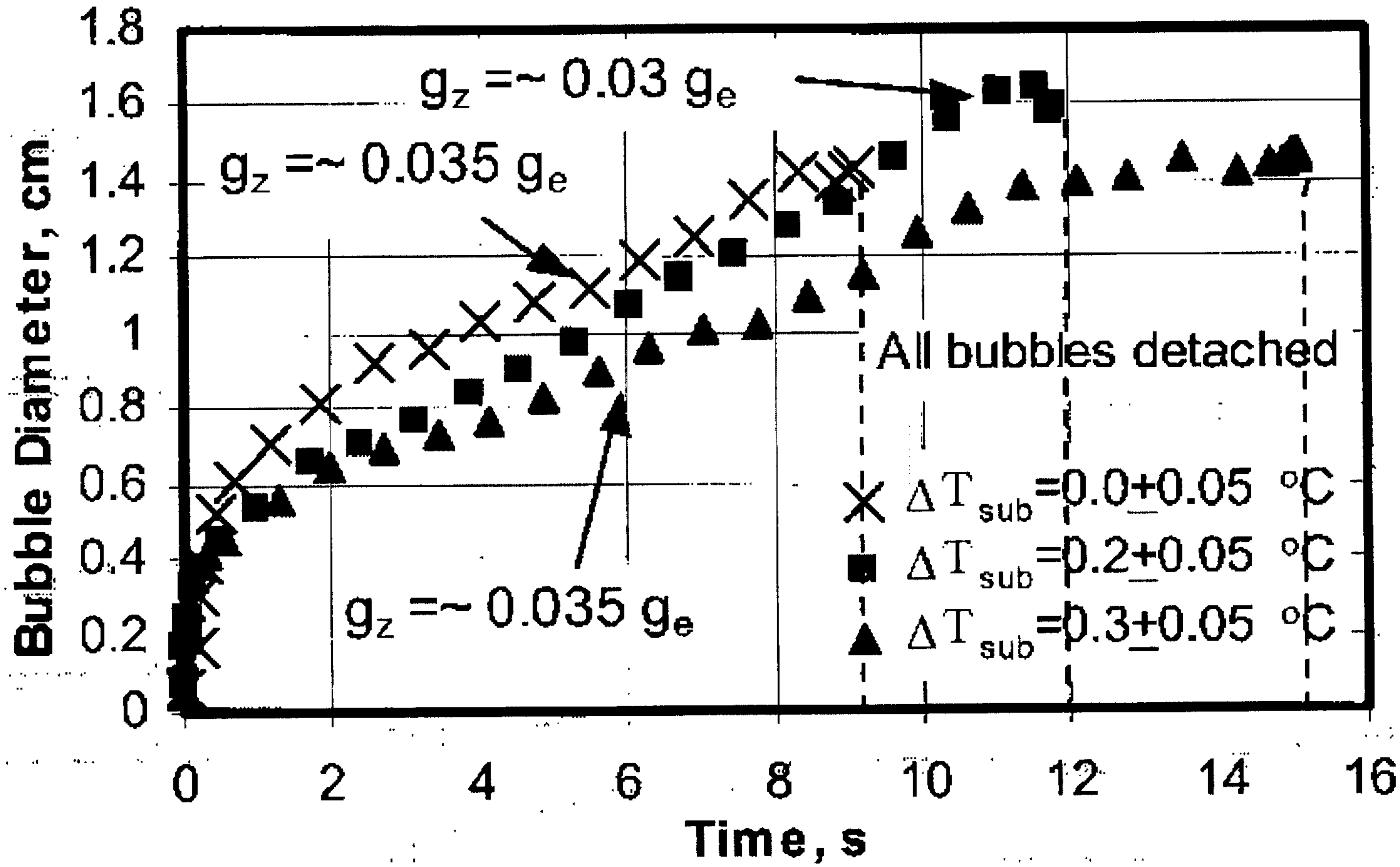
EXPERIMENTAL RESULTS (Cont'd)

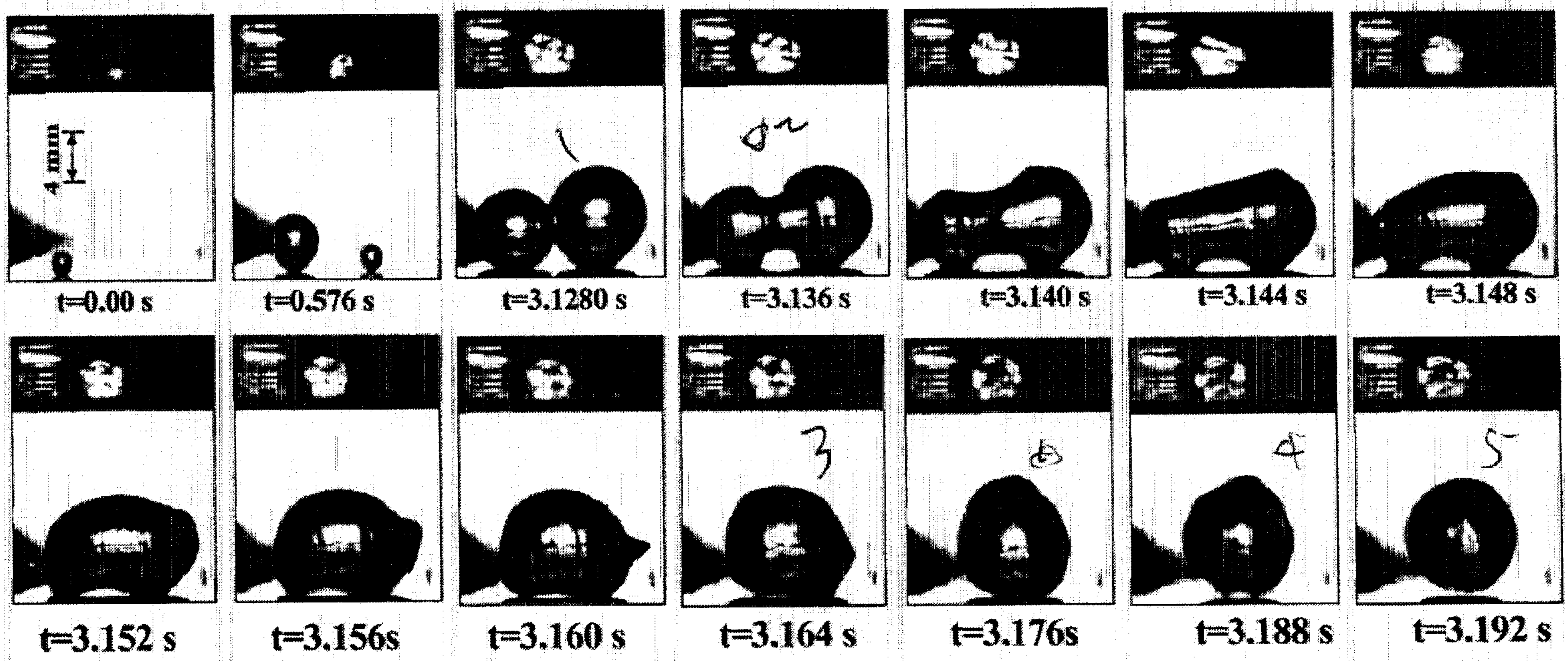
-- Single Bubble at Low Gravity in KC-135



Effect of Liquid Subcooling on Bubble Growth for a Wall Superheat T_w-T_{sat}=3.5 °C

EXPERIMENTAL RESULTS

-- Horizontal Merger of Two Bubbles at Low Gravity



Two Bubble Merger at ΔT_{sub}=3.0 °C, T_w-T_{sat}=5.0°C,
g_z=0.0033 g_e, g_x=0.0060 g_e, g_y=–0.0009 g_e

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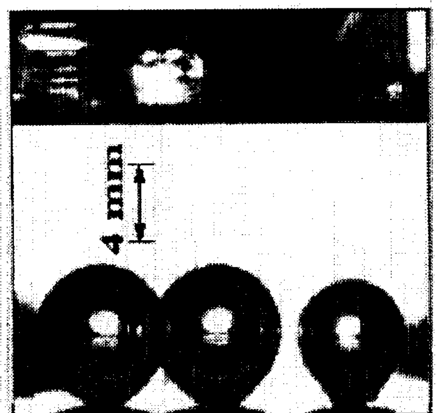
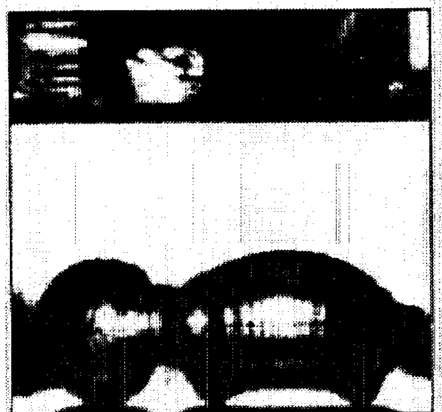
EXPERIMENTAL RESULTS (Cont'd)

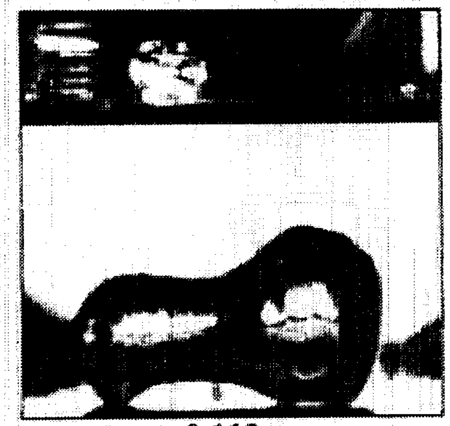
-- Horizontal Merger of Three Bubbles at Low Gravity



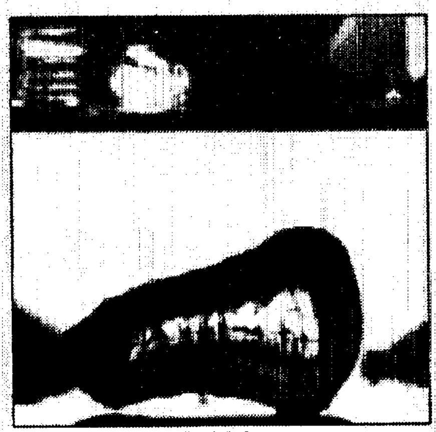
t=0.000 s



t=0.096 s



t=0.112 s



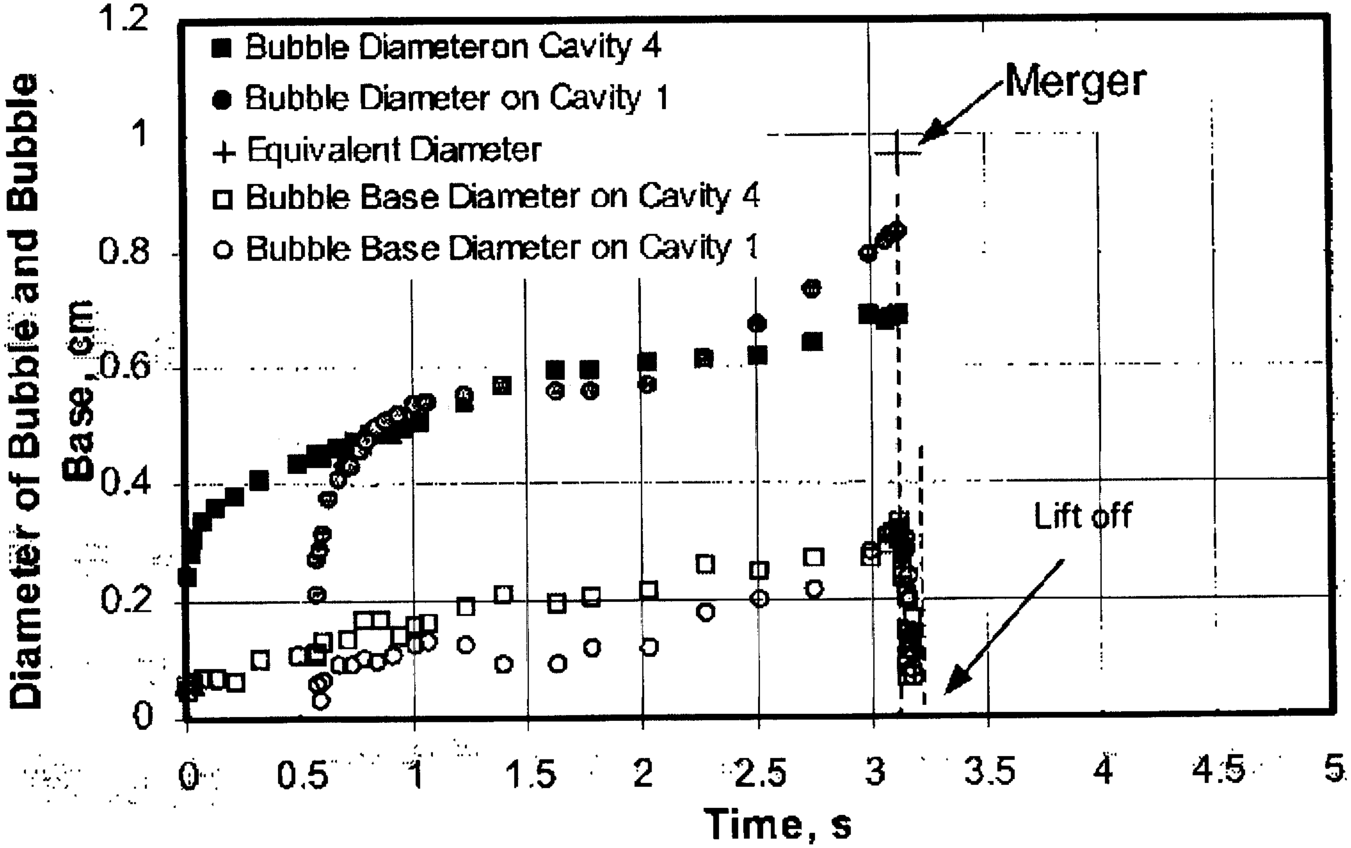
t=0.120 s

t=0.128 s

Three Bubble Merger at ΔT_{sub}=2.0 °C, T_w-T_{sat}=5.5°C,
g_z=0.008 g_e, g_x=0.003 g_e, g_y=~0.000 g_e

EXPERIMENTAL RESULTS (Cont'd)

-- Horizontal Merger of Two Bubbles at Low Gravity



Diameter of Bubbles and Bubble Bases during Two Bubble Merger at ΔT_{sub}=3.0 °C, T_w-T_{sat}=5.0°C, g_z=0.0033 g_e, g_x=0.0060 g_e, g_y=-0.0009 g_e

COMPARISON OF NUMERICAL SIMULATIONS WITH EXPERIMETAL RESULTS

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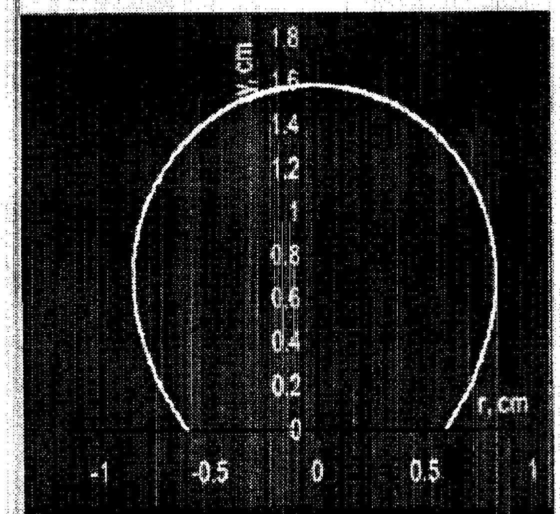
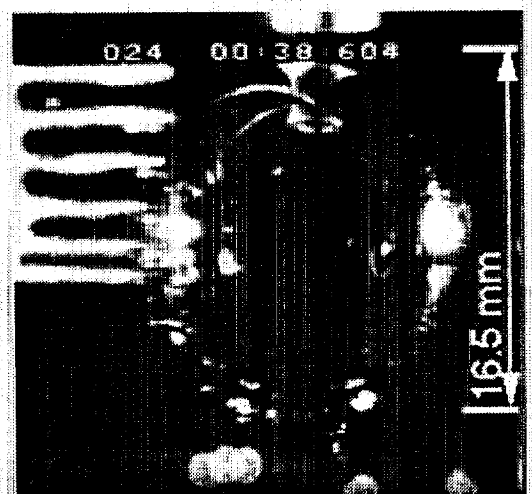
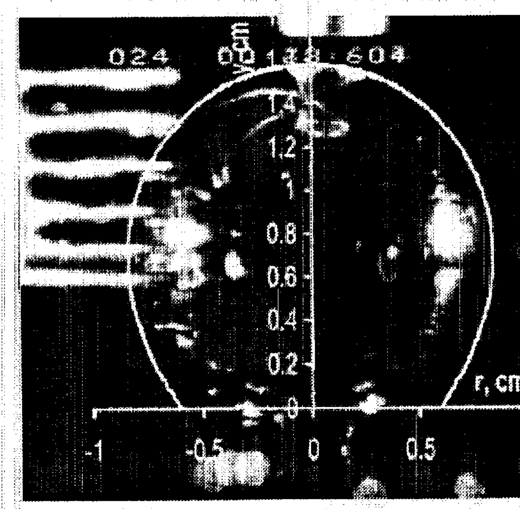
Comparison of Numerical Simulation Results with Data in Subcooled Water -- at Low Gravity



Numerical



Experimental



Comparison

$g = 0.02\ g_e$, $T_w\text{-}T_s = 3.8\ ^oC$, $\Delta T_{sub} = 0.4\ ^oC$

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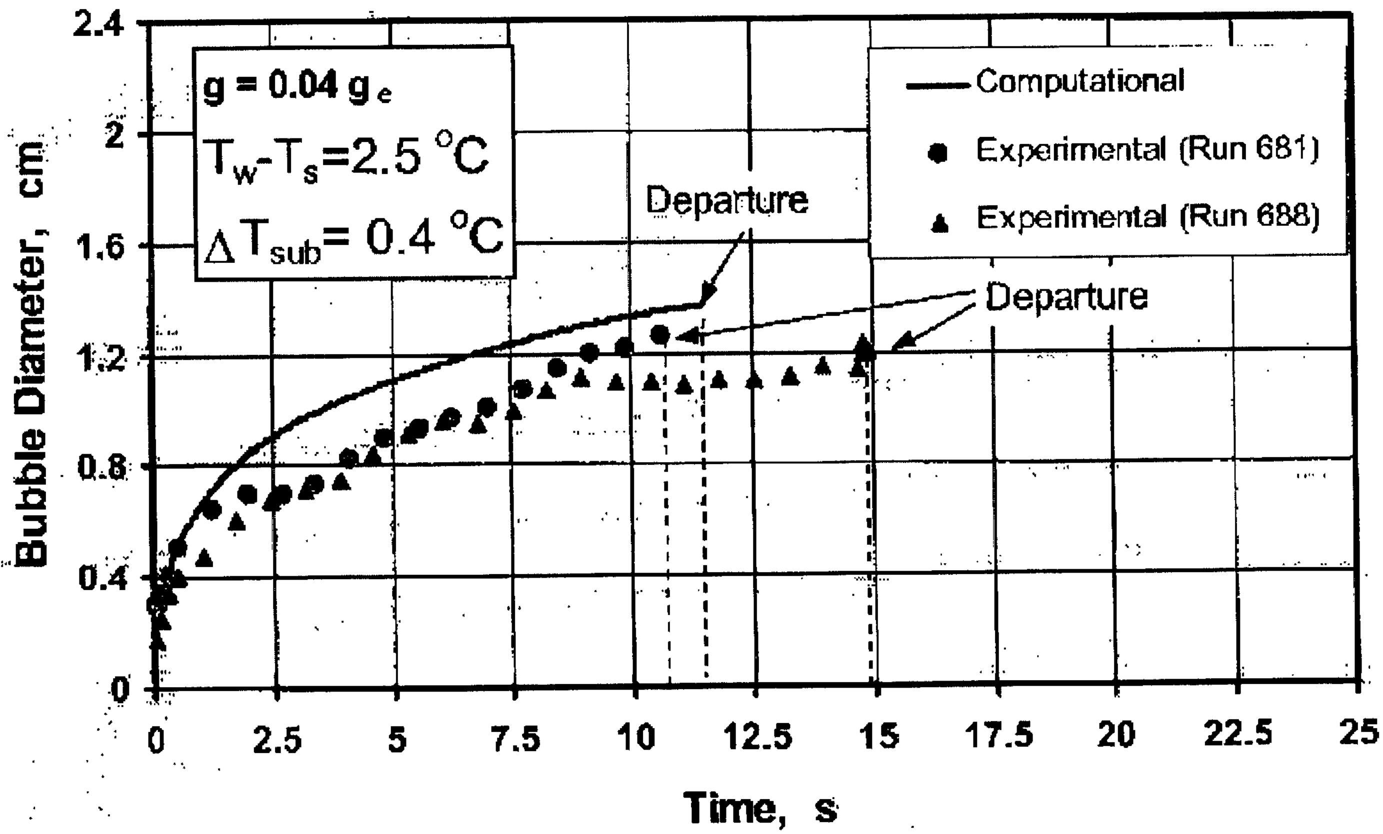
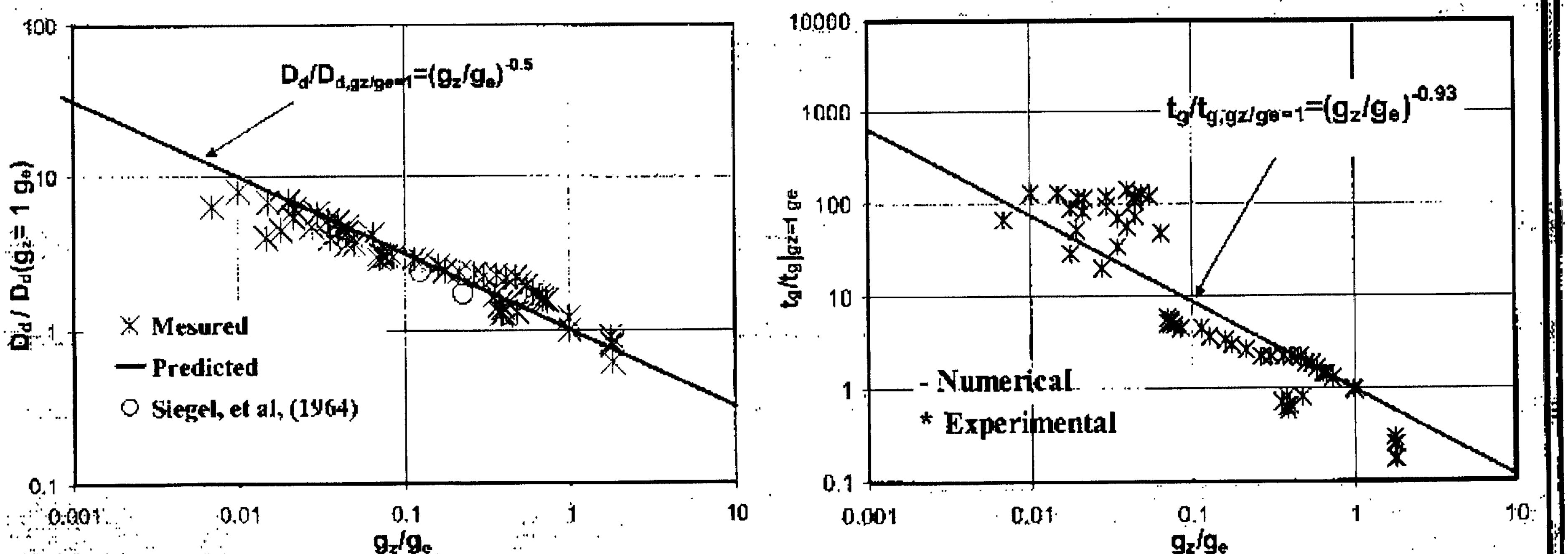
Comparison of Numerical Simulation Results with Data in Subcooled Water (Cont'd) -- at Low Gravity



SCALING OF EFFECT OF GRAVITY ON SINGLE BUBBLE DEPARTURE (Cont'd)



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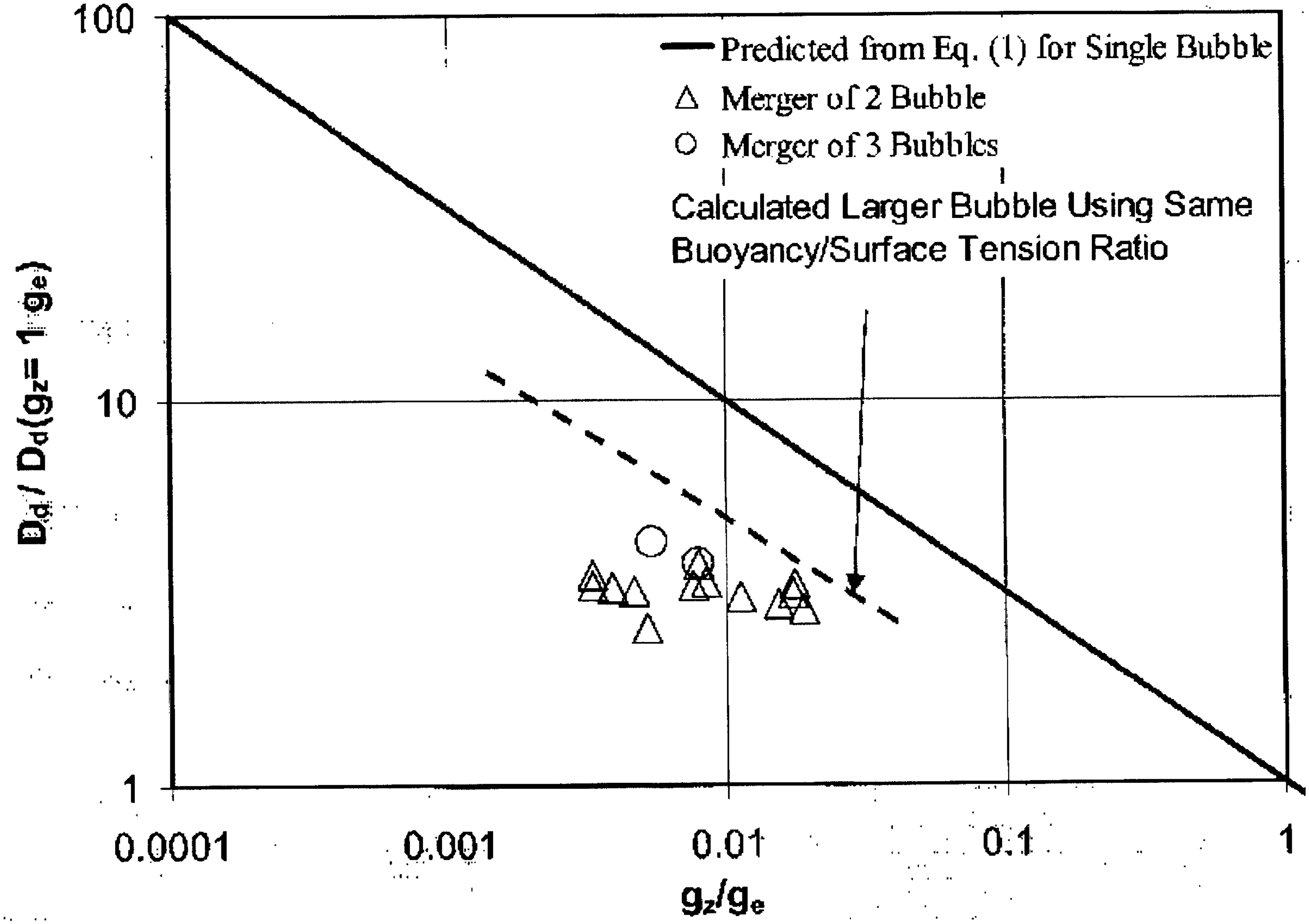
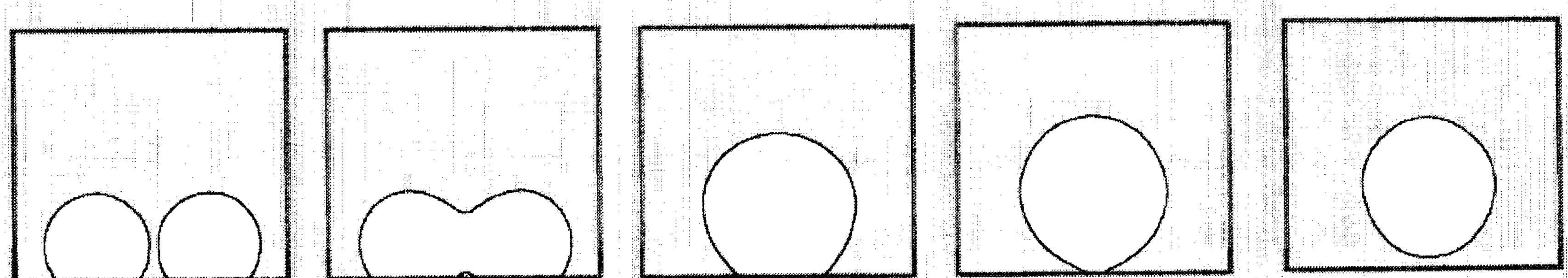
EXPERIMENTAL RESULTS (Cont'd)

-- Horizontal Merger of 2 and 3 Bubbles at Low Gravity



Comparison of Numerical Simulation Results (3-D) with Experimental Data

Experimental



Numerical

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CONCLUDING REMARKS

- Well defined and controllable nucleation sites were obtained by micro-fabricating cavities on the polished Silicon wafer.
- Complete boiling process of single bubble from nucleation inception to departure of bubble was observed on the designed surface at low gravity.
- Larger bubble departure diameters (> ~20 mm) and longer bubble growth periods than those at earth normal gravity were measured.
- The bubble departure diameters and growth periods scale as

  $D_d \propto g^{-1/2}$ and $t_g \propto g^{-0.93}$ respectively.
- Small subcooling in the liquid can lead to significantly prolonged bubble growth periods and reduced bubble growth rates.
- During bubble merger, mushroom type of bubbles attached to the heater surface via vapor stems were observed to form.
- The merger caused lift-off of the vapor mass from the surface in a smaller equivalent diameter than that of a single bubble at departure at the same gravity level.
- The liquid motion during merger and the resulting lift force probably played a role in early lift-off of the merged bubbles.